THICKNESS DESIGN CALCULATIONS FOR THE NEW LARGE AIRCRAFT (NLA) AIRBUS A380

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ABSTRACT

The arrival of the Boeing B777, which has 6-wheel landing gears, and proposals for new large aircraft (NLA) have focused attention on thickness-design calculations, which must now take into account these large, multi-wheeled, gear characteristics. It is well known that the current pavement-design procedures do not accurately predict the load interaction of closely spaced landing gears on these new-generation aircraft. Thus it is not always evident that the conventional FAA procedure, which is based on the U.S. Army Corps of Engineers (USACE) procedure for calculating pavement thicknesses, is correct for these new types. This uncertainty is supported by the fact that thickness-design curves have not yet been included in the preliminary technical publication for the Airbus A380. In this context, it should be added that the construction of the National Airport Pavement Test Facility (NAPTF) in Atlantic City (NJ, USA) was based on the need for developing new design procedures for the new types of aircraft. In the meantime, however, the construction of new airport pavements, particularly new runways and aprons, has to continue although the predicted fleet-mix includes the new large aircraft (NLA). Thus for the intermediate period, approximate procedures are suggested for calculating the pavement-thickness values for NLA's, particularly the forthcoming Airbus A380. The derived CBR design equations are compatible with the reduced values of the published Aircraft Classification Number (ACN). One of these equations is based on a recent, different interpretation of the historical MWHGL tests that the U.S. Army Corps of Engineers conducted some 35 years ago. To conclude, the new equations lead to smaller thicknesses compared with those calculated by the derived conventional FAA equation. The new equations have recently been utilized for upgrading runways at Israel's Ben-Gurion International Airport.

Keywords: Aircraft Classification Number (ACN), New Large Aircraft (NLA), Pavement design, Pavement thickness, Regression analysis, Runway.

INTRODUCTION

The recent arrival of the Boeing B777, which has 6-wheel landing gears (see Fig. 1), and proposals for new large aircraft (NLA) have focused attention on thickness-design calculations, which must now take into account the large, multi-wheeled, gear characteristics of these airplanes. It is well known that the current pavement-design procedures do not accurately predict the load interaction of closely spaced landing gears on this new-generation of aircraft. Thus it is not always evident that the conventional FAA procedure, which is based on the U.S. Army Corps of Engineers (USACE) procedure for calculating pavement thicknesses, is correct for these new types of aircraft.

This uncertainty has been supported by the fact that thickness-design curves have not yet been included in the preliminary technical publication for the Airbus A380, entitled "A380 Airplane Characteristics for Airport Planning." This publication did include, however, the Aircraft Classification Number (ACN) values required for the actual operation of this type craft at existing airports [1].

In this context, it should be added that the construction of the National Airport Pavement Test Facility (NAPTF) in Atlantic City (NJ, USA) was based on the need for developing new design procedures for large aircraft types still to come [2, 3]. In the meantime, however, the construction of new airport pavements, particularly new runways and aprons, has to continue although the predicted fleet-mix includes the new generation of new large aircraft (NLA). Thus it is important in this intermediate period to find an approximate procedure for calculating pavement-thickness values for NLA's, particularly for the forthcoming Airbus A380, that will be compatible with published ACN values.

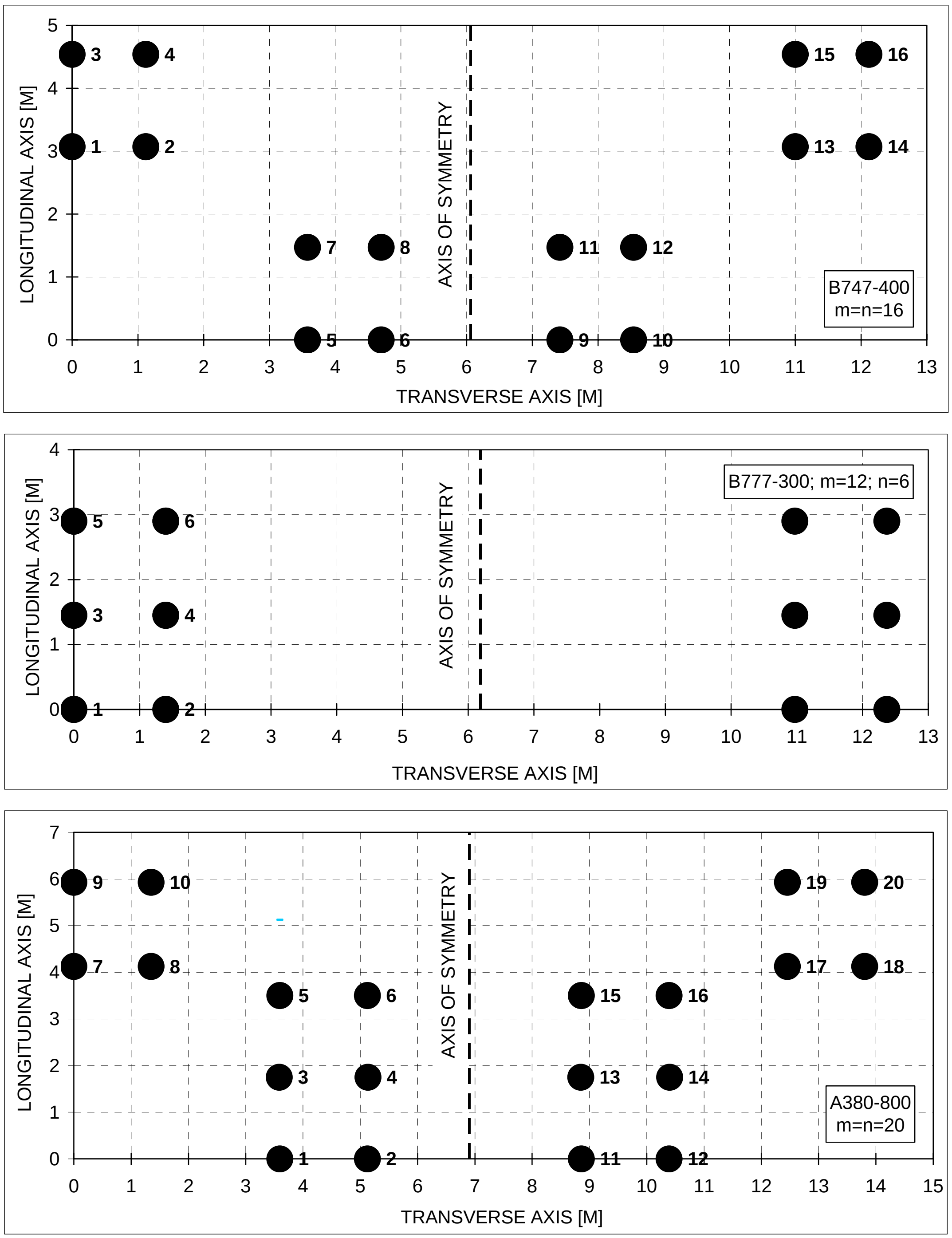

Figure 1. Main landing-gear (both wing and body landing gears) configuration for the B747, B777, and A380 aircraft (not to scale).

The main objective of this paper is to develop approximate equations to calculate the flexible pavement thicknesses for the forthcoming Airbus A380. Obviously these equations should comply with the published ACN values for these type aircraft.

EMPIRICAL FAA DESIGN METHOD

The empirical FAA design methodology (also called the conventional FAA method, or the conventional USACE method), for the structural design of flexible aircraft pavement [4] was calibrated against the USACE full-scale trafficking tests (known as the MWHGL tests), conducted almost 35 years ago [5]. This FAA design procedure involves various simplifying assumptions in the calibration process, the major assumptions relating to the use of the single-layer elastic theory and the deflection-based Equivalent Single Wheel Load concept for multiwheel aircraft gear. The flexible design curves for this method are also based on procedures set forth in Instruction Report No. S-77-1, issued by the U.S. Army Corps of Engineers [6]. In its original form, the mathematical expression of these design curves is given in English units. From this original expression the following one can be derived for other units such as mm and kg:

$$Z_A = \alpha \times \sqrt{\frac{100 \times \mathrm{ESWL}}{0.5695 \times \mathrm{CBR}} - \frac{A}{\pi}} \qquad (1)$$

where:

Z_A= pavement-design thickness, in mm, above the subgrade, for given aircraft and coverages;

A= tire contact area equals to that of one wheel of an airplane's main gear assembly, in mm^2;

ESWL= equivalent single-wheel load, in kg, with a contact area of A, which produces the same deflection at a specific depth as does the given main gear assembly (see Fig. 2 for illustrative variations of ESWL with depth);

CBR= subgrade California Bearing Ratio (not in excess of 15), as a percentage;

α= load-repletion factor as selected from Fig. 3 for a given number of wheels, n, used to compute ESWL.

The conventional FAA design method is also used for calculating the ICAO's Aircraft Classification Number (ACN), which expresses an airplane's relative structural effect on different pavement types for specified standard subgrade strengths in terms of a standard single-wheel load. Specifically, ACN is numerically defined as two times the derived single-wheel load (DSWL), which produces the same deflection at a specific depth, as does an airplane's main gear assembly and which is expressed in thousand of kg. It should be noted that this derived single-wheel load also has a fixed contact pressure of 1.25 MPa.

Essentially, the ACN calculation procedure is as follows: (a) for the specific aircraft, the load on each main gear at maximum gross take-off weight is determined according to the percentage distribution of the most aft center of gravity; (b) the number of coverages is set at 10,000 and the corresponding load-repetition factor, α, is selected from Fig. 3 for the given number of wheels, n, used to compute ESWL; (c) pavement thicknesses are determined for a range of CBR values (3%, 6%, 10%, and 15%) according to the conventional FAA procedure (Eq. 1); finally (d) the

ACN value (which is equal by approximation to 2×ESWL, instead of 2×DSWL) is determined from the following expression:

$$\mathrm{ACN}=\frac{\dfrac{Z_A^{\,2}}{100{,}000}}{\dfrac{0.878}{\mathrm{CBR}}-0.01249} \qquad (2)$$

where:

Z_A= pavement-design thickness, in mm, calculated from Eq.1 for specific CBR values (e.g., 3%, 6%, 10% or 15%) at 10,000 coverages;

CBR= one of the above specific values of the subgrade California Bearing Ratio, as a percentage.

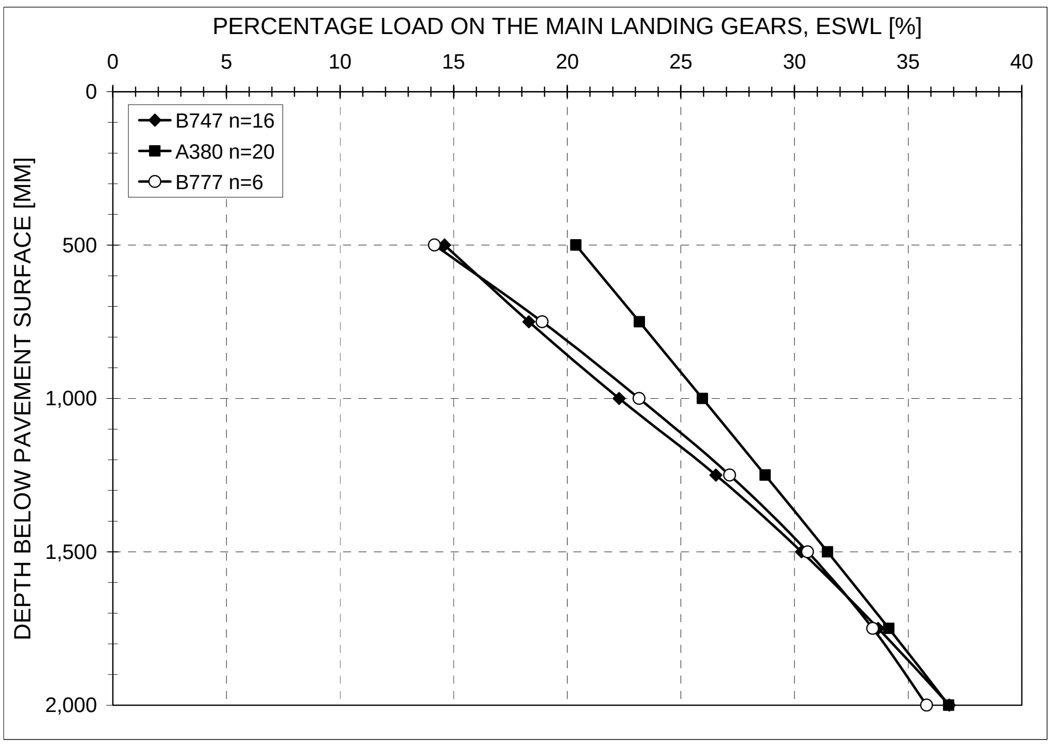

Figure 2. Equivalent single-wheel load versus depth below pavement surface for the B747, B777, and A380 aircraft.

Finally, it should be mentioned that the FAA has recently developed a mechanistic method that is based on the indirect calibration of a layered elastic analysis against the same limited, full-scale, historical MWHGL tests used to produce the above-mentioned empirical pavement-design method. The mechanistic method incorporates a computer program called LEDFAA. The derivation of LEDFAA through indirect calibration was conditioned on mandating certain input material properties to produce, for typical airplane-traffic mixes, similar pavement thickness to those obtained by using the conventional FAA design method [7]. For example, in order to better align the LEDFAA and FAA conventional thicknesses, asphalt surfacing was assigned a constant stiffness of 1,380 MPa. This value is a very low one for environments with moderate and cool temperatures, especially for thick asphalt layers. At the present time, changes made to the mandated inputs render the design "non-standard" for the purpose of FAA funding approvals; the designer needs to argue the reasonableness of the changes [8]. For these reasons, it is postulated later in the paper that, the LEDFAA procedure is not an adequate substitute for the FAA conventional procedure for the A380 aircraft if the latter procedure fails to yield reasonable answers.

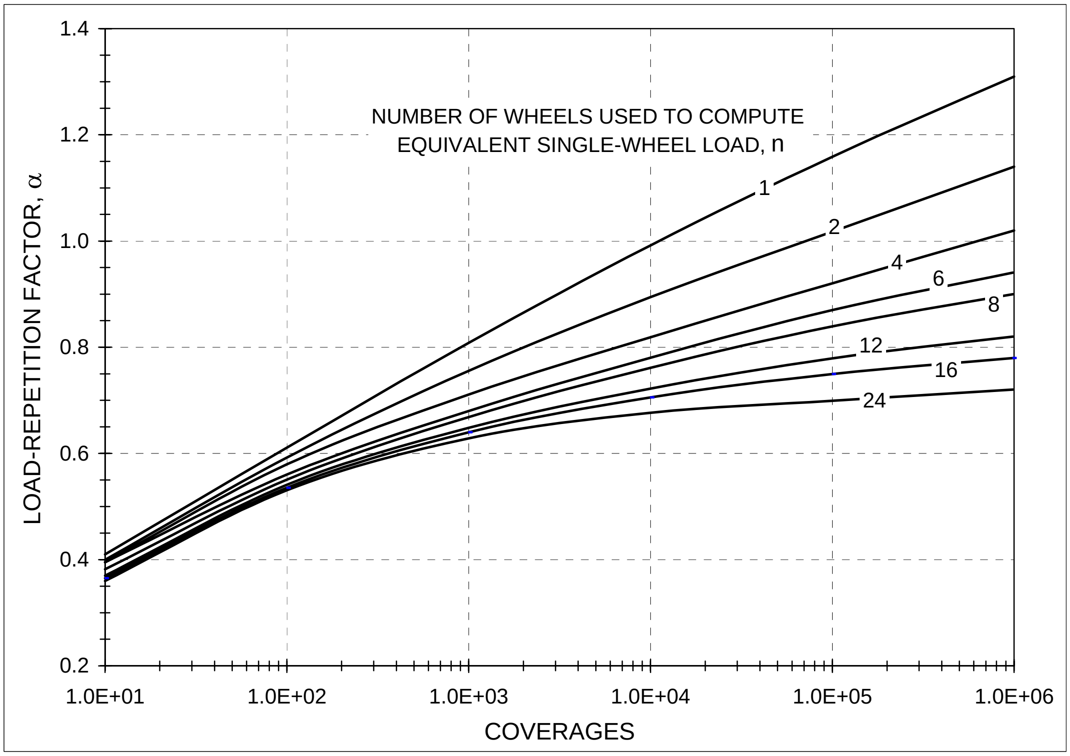

Figure 3. Load-repetition factor, α, versus coverages.

OUTPUTS FOR A380 AIRCRAFT

As mentioned, design curves were not yet been included in the preliminary technical publication entitled "A380 Airplane Characteristics for Airport Planning" [1]. Thus, use is made here of Eq. 1 to calculate pavement-design curves for this aircraft. In this calculation the following data were utilized: (a) airplane maximum weight of 1,305,000 lbs, (b) percentage weight on main landing gear of 95.01%, (c) pass-to-coverage ratio of 1.54, and (d) tire contact area of one wheel of the main gear assembly of 20,718 mm^2. In addition, the required load-repetitions factor, α, versus number of coverages was taken from Fig. 3 for a total number of landing wheels used to compute ESWL of 20 (i.e., the n value for Fig 3 equals 20; see also Fig. 1), and the required ESWL versus depth from Fig. 2 for the A380 aircraft.

The derived design curve for 120,000 repetitions (i.e., 6,000 annual departures along a design period of 20 years) is displayed in Fig. 4. For comparison purposes, the design curve for the B747 aircraft is also included in the figure.

Fig. 4 indicates that the pavement-thickness design for the A380 maximum weight leads to significantly higher thickness values than those calculated for the B747 maximum weight. If this phenomenon is correct, existing pavements that have been designed for the B747 loadings may require immediate strengthening in order to accommodate the A380 loadings. It should be noted that the same argument was also found for the B777 aircraft [9].

In addition to the above-mentioned thickness calculations, ACN values were derived from Eq. 2. The values obtained for the maximum weight of the A380-800 airplane are shown in Table 1. Also shown in the table are the ACN values reported by the manufacturer [1].

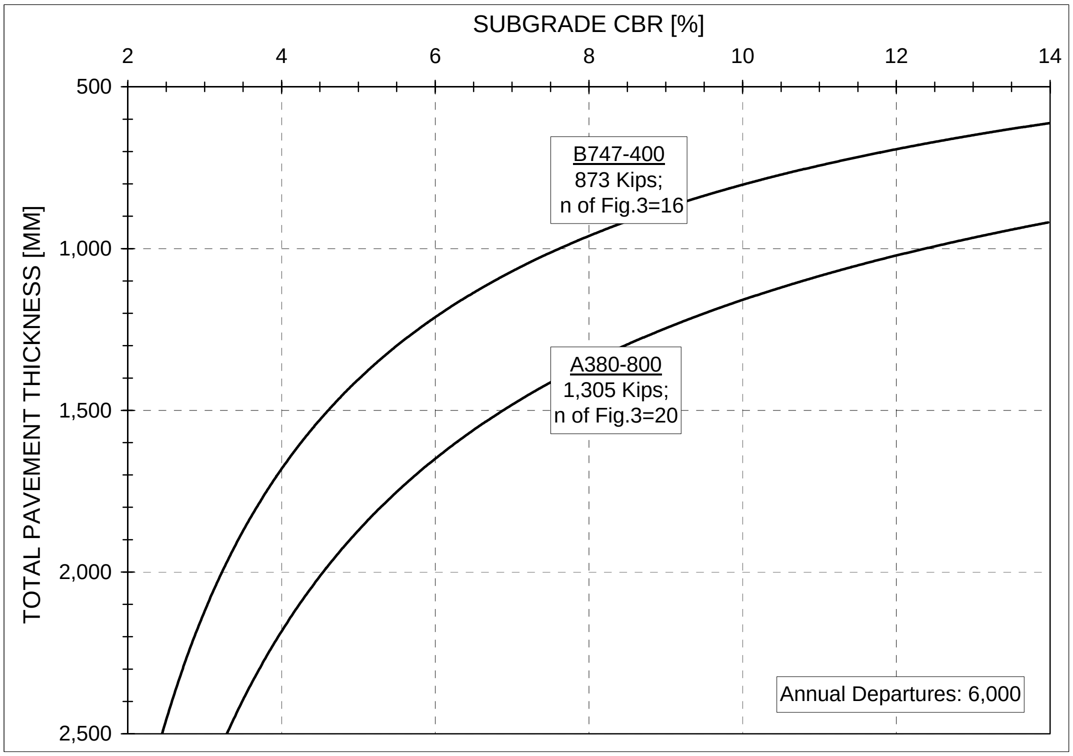

Figure 4. Pavement-design curves for the A380 and A747 aircraft as derived from Eq. 1 for maximum weight and 120,000 repetitions.

For comparison purposes, the ACN values of the B747-400 airplane are also included in Table 1 [10]. The deviations of the calculated ACN values from those reported for this airplane stem from the various approximations made in the calculation procedure described above. For this airplane, the maximum ratio of the calculated ACN to the reported ACN is 1.3. For the A380-800, however, the above deviations values are much higher, with the maximum ratio of the calculated ACN to the reported ACN mounting up to 2.3.

The above deviations for the ACN values lead to the conclusion that the empirical FAA design method for the A380 airplane (Eq. 1) is not compatible with the manufacturer-reported ACN values as given in Table 1. Moreover, it may be concluded that the required pavement thickness that is compatible with the above-reported ACN values is smaller than that derived from Fig. 4.

In this context it should be mentioned that the same phenomenon characterizes pavement design for the B777-300 airplane. The empirical FAA design method shows that this type aircraft is more critical than the B747-400. This fact led the ICAO-ACN Study Group to introduce an interim α factor of 0.72 for reducing the calculated ACN values obtained for the B777-300 [8, 11, 12]. In contrast to the latter reduced ACN values, the procedure that led to the present reduced ACN values for the A380-800 (i.e., the ACN values given in Table 1 as reported by the manufacturer) has not yet been published by the manufacturer.

Table 1. Reported and calculated ACN values.

Airplane	Maximum Weight [Kips]	ACN Source	Subgrade CBR Value [%]			
			3	6	10	15
A380-800	1,035 (n of Fig. 3=20)	Reported	118	87	72	65
		Calculated	225	189	165	151
B747-400	873 (n of Fig. 3=16)	Reported	102	79	64	57
		Calculated	135	98	77	64

NEW, SIMPLIFIED CBR DESIGN EQUATIONS

It has been shown elsewhere [13] that it is preferable to calculate the required Z_A value of Eq. 2 according to a simplified CBR design equation. This equation is based on a direct, advanced regression analysis on the historical MWHGL test data for the single, twin-tandem, and twelve-wheel assembly configurations [9, 14, 15]. The regression analysis involved the directly tested parameters that served the full-scale experiments. In other words, the independent variables utilized in the regression analysis were these: (a) airplane weight on main landing gear, (b) number of total wheels in the main landing gear, (c) a recorded number of airplane coverages to failure, and (d) two major characteristics of the pavement tracks tested (subgrade CBR and total pavement thickness). Thus, unlike the FAA conventional CBR design equations (i.e., the USACE CBR design equations), the suggested regression analysis is not intended to involve the use of either the equivalent single-wheel load (ESWL) concept or any pre-determined-thickness CBR model.

In order to eliminate any doubt, it should be emphasized that the suggested new CBR design equation is not based on the outputs of the existing FAA conventional CBR design equations or charts, but on the original testing data alone. Obviously this original, full-scale testing data served primarily to derive the existing conventional FAA design method. Thus both the conventional FAA and the new equations constitute different interpretations of the same full-scale testing data. In other words, the proposed equation is different conceptually from the conventional FAA method, not only because of the dissimilarity in their formats.

The new regression equation obtained from the above-mentioned analysis is given by the following expression for which R^2=0.967 and number of observation=27:

$$Z_R = 35.0 \times [g_m \times \log(C) \times \frac{9.81 \times 0.5 \times L_m}{CBR}]^{0.594} \tag{3}$$

where:

Z_R = design-pavement thickness, in mm, as obtained from the direct-regression method;

L_m = airplane weight on main landing gear, in 1,000 kg;

C = number of airplane design coverages;

CBR = California Bearing Ratio of the subgrade soil, as a percentage;

g_m = a function depending on the number of total wheels in the main landing gear (i.e., total number of wheels of any given airplane minus the nose wheels), m (and not n; see also Fig. 1), as follows (in a logarithmic form):

$$\log(g_{m}) = -0.4025 \times \log(\frac{m}{2}) \times (\frac{m}{2})^{0.2464} \tag{4}$$

At this juncture, it should be noted that Eq. 3 was further modified in the following manner for aircraft containing 12 or more wheels in their main landing gear (i.e., m≥12):

$$Z_M = \lambda \times Z_R{}^{\eta} \tag{5}$$

where:

Z_M = design-pavement thickness, in mm, as a modification of the direct-regression method;

Z_R = unmodified design-pavement thickness, in mm, as obtained from the above direct-regression method (Eqs. 3 and 4);

λ, η = modifying parameters as a function depending on the number of total wheels in the main landing gear, m, as follows:

$$\lambda=-0.1584\times(m/10)^2+0.6061\times(m/10)-0.3380 \tag{6}$$

$$\eta=0.0750\times(m/10)^2-0.3132\times(m/10)+1.5231 \tag{7}$$

In conjunction with Eqs. 6 and 7, it should be noted that $\lambda=\eta=1$ for aircraft containing 8 or fewer wheels in the main landing gear. Finally, in order to calculate the ACN number for a given aircraft, Z_M for C=10.000 is substituted for Z_A in Eq. 2.

The comparison study for the B747, B777, and A380 aircraft is shown in Fig 5. The calculated ACN values in this figure are those derived from the suggested approximate method shown by Eq. 3 to Eq. 7, in which the total number of wheels in the main landing gear, m, is as follows: 16 for the B747, 12 for the B777, and 20 for the A380; also, C=10,000. As mentioned, the reported ACN values in this figure are the ones published by the aircraft manufacturers themselves [1, 10, 13].

Fig. 5 indicates that the suggested approximate method for calculating the ACN values for the NLA's yields reasonable results. In other words, Fig. 5 indicates that the suggested approximate procedure for calculating ACN values for NLA's may replace the conventional FAA method, which does not conform to the manufacturers' reduced ACN values.

The above findings may also lead to the conclusion that Eq. 3 to Eq. 7 may be used for calculating pavement thickness for any given NLA loadings and any given subgrade CBR value. This is dealt with in the next section.

SUGGESTED DESIGN EQUATIONS FOR A380 AIRCRAFT

The previous section suggested that Eq. 3 to Eq. 7 may be used for calculating pavement thickness for any given NLA loadings (particularly for the B777 and A380 aircraft) and any given subgrade CBR value. Thus, it is interesting to compare the flexible pavement thickness derived by the conventional FAA method with that derived from the new approximate method outlined in the previous section. Table 2 displays these thickness results for a subgrade CBR of

4.5% and 6,000 annual departures over a design period of 20 years. It should be noted that these calculations were made for (a) airplane maximum weight and (b) the following pass-to-coverage ratios: 1.74 for the B747, 1.34 for the B777, and 1.54 for the A380.

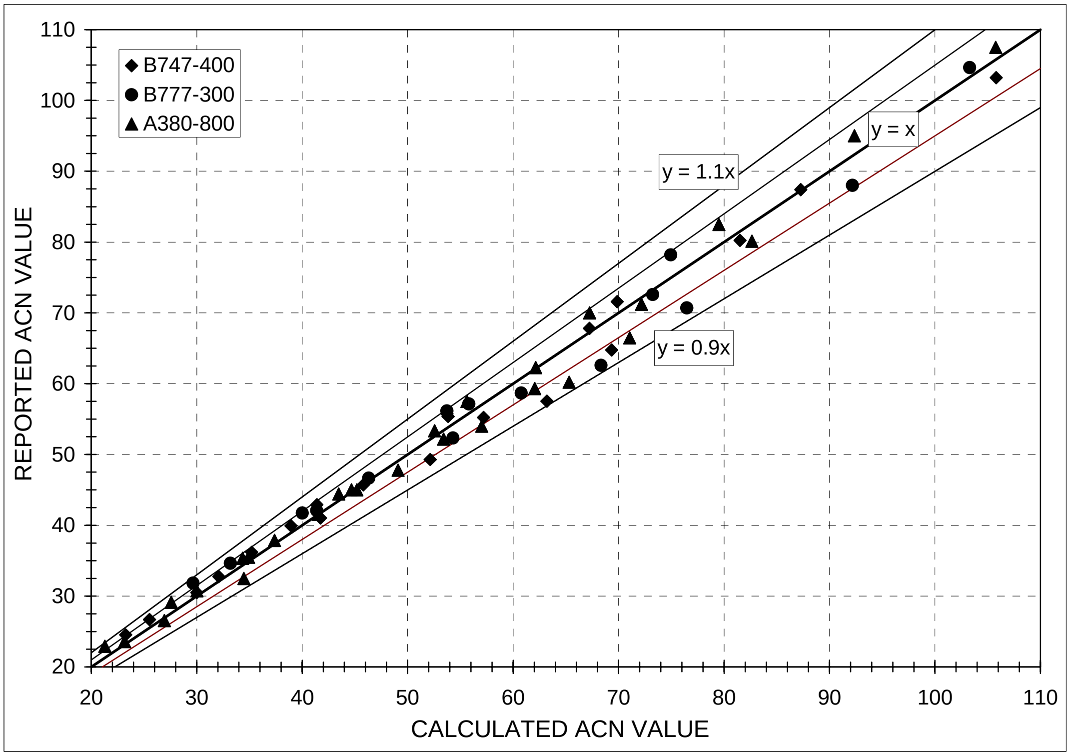

Figure 5. Reported ACN versus approximate calculated ACN for the B747-400, B777-300, and A380-800 aircraft.

Table 2. Total thickness results for the B747, B777, and A380 aircraft.

Aircraft	Max Weight [Lbs]	Total Thickness [mm] for a Subgrade CBR of 4.5% and 6,000 Annual Departures (20 Years)		Thickness Ratio [(b)/(a)]
		(a): FAA Eq. 1	(b): Eq. 3 to Eq. 7	
B747-400	873,000	1530	1480	0.97
B777-300	662,000	1620	1440	0.89
A380-800	1,305,000	2000	1570	0.79
Note: The thickness values for the B747-400 and the A380-800, derived from Eq. 1, are also given in Fig. 4.				

Again, Table 2 indicates that the conventional FAA method leads to a remarkably higher total pavement thickness for both the B777 and the A380. As for the B747, the new approximate method outlined in this paper leads practically to the same thickness values given by the conventional FAA method. Thus, the National Airport Pavement Test Facility (NAPTF) in Atlantic City will, it is planned, develop new design procedures for the new B777 and A380 types of aircraft. In the meantime, the construction of new airport pavements, especially for runways and aprons, has to continue although the predicted fleet-mix does include the new generation of large aircraft (NLA). Therefore, it is suggested that the new approximate procedure for calculating the total pavement thickness values for the NLA's, in particular for the forthcoming Airbus A380, be implemented during this intermediate period.

For the A380 airplane, the new approximate equations for calculating the total pavement-thickness values (Eq. 3 to Eq. 7) may be reduced to the following single equation:

$$Z_M = 0.2405 \times \{35.0 \times [0.19505 \times \log(\frac{D}{1.54}) \times \frac{9.81 \times 0.5 \times L_m}{CBR}]^{0.594}\}^{1.1966} \qquad (8)$$

where:

Z_M = new suggested pavement-design thickness, in mm, for the A380;

L_m = weight on main landing gear of A380, in 1,000 kg;

D = number of A380 design departures;

CBR = California Bearing Ratio of the subgrade soil, as a percentage;

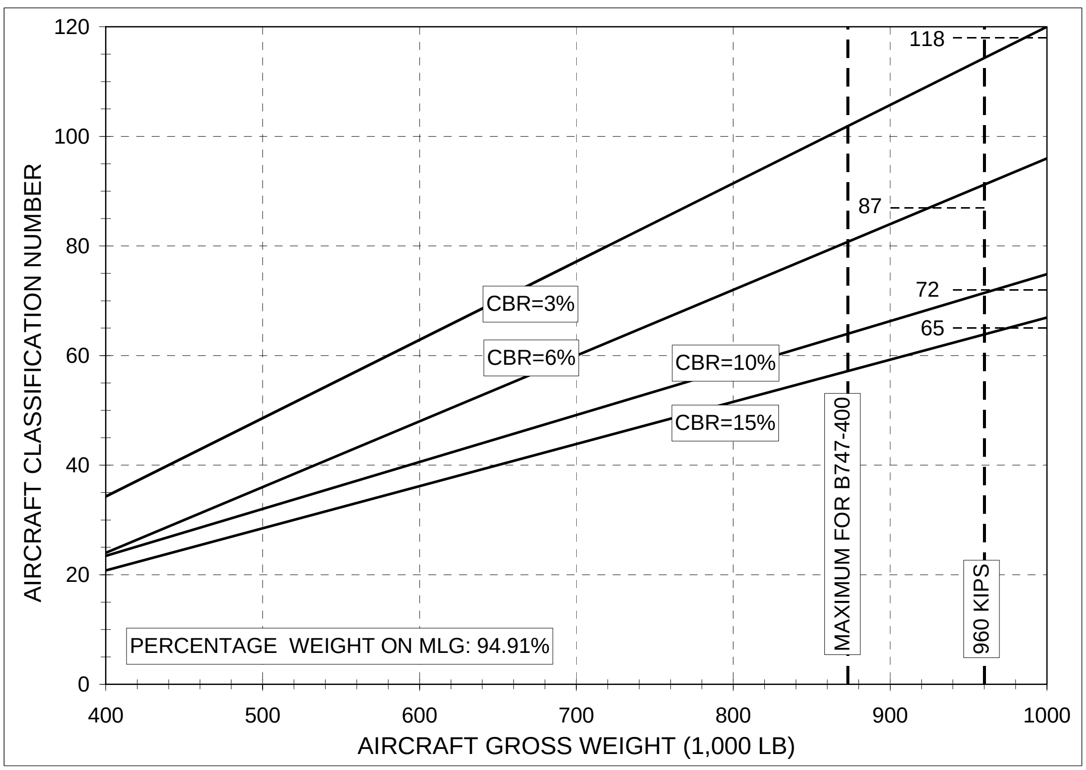

Figure 6. ACN values versus gross weight of B747-400 for deriving the equivalent maximum gross weight in the ACN equivalent method for the A380-800.

Obviously, Eq. 8 assumes that the manufacturer reduced ACN values are correct. Even so, the reasonableness of Eq. 8 should be checked against that of another alternative procedure for calculating total pavement thicknesses for the A380 airplane. This alternative procedure is based on the conventional FAA method for the B747, with an enlarged total weight employed to equalize the B747's ACN values to the reported A380's ACN values (a procedure also termed the ACN equivalent procedure). It can be concluded from Fig. 6 that the enlarged total weight is equal to about 960,000 lbs. For this weight (termed the equivalent total weight) the conventional

FAA method leads to the following result for 6,000 annual departures over a design period of 20 years:

$$Z_F = 4335.6 \times CBR^{-0.7254} \tag{9}$$

where:

Z_F = conventional FAA pavement-design thickness, in mm, for the B747, with an enlarged total weight (960 kips) representing the A380 (i.e., ACN equivalent pavement-design thickness for the A380, with maximum gross weight and 6,000 annual departures over a design period of 20 years);

CBR = California Bearing Ratio of the subgrade soil, as a percentage;

For comparison purposes, Fig. 7 displays the following pavement-design curves for the A380 aircraft characterized by a maximum gross weight of 1,305 kips and 6,000 annual departures over a design period of 20 years: (a) according to Eq. 8, which is based on the new correlative equations (Eq. 3 to Eq. 7) for the A380, (b) according to Eq. 9, which is based on the FAA conventional method (Eq. 1) for the B747, with an enlarged total weight (960 kips) to represent the A380 (i.e., the ACN equivalent method); and (c) according to the FAA conventional method (Eq. 1), which is based on the ESWL calculations (Fig. 2) for the A380 at its maximum gross weight. The last curve is also plotted in Fig. 4.

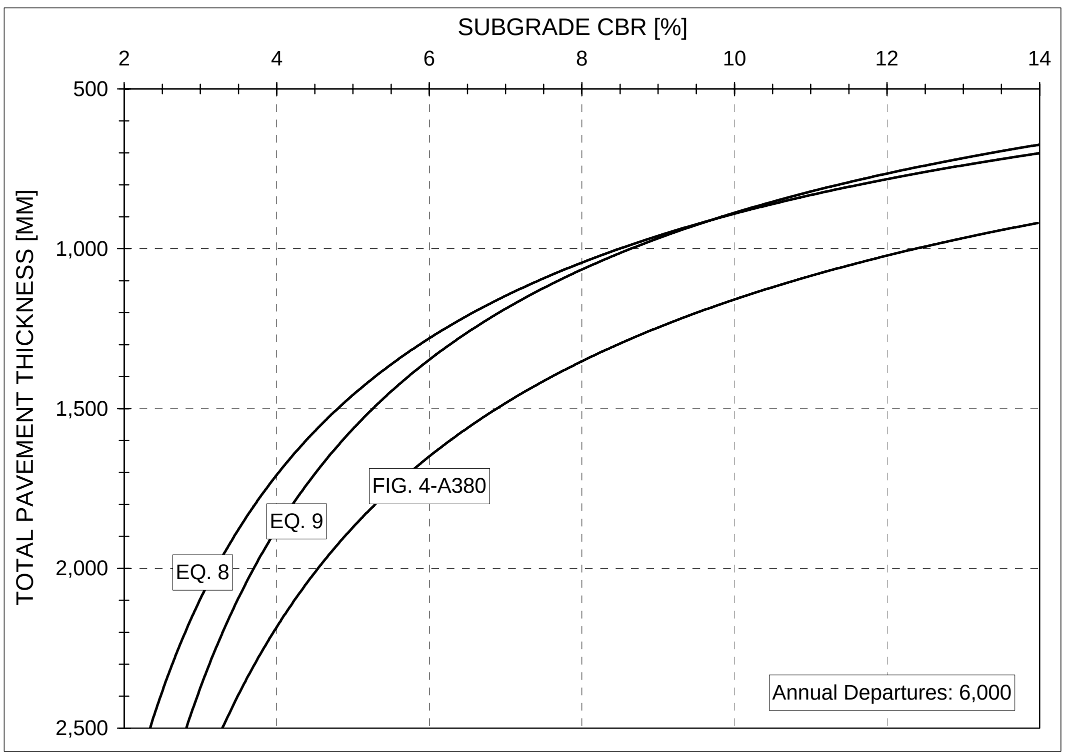

Figure 7. Comparison of pavement design curves for the A380-800 aircraft with maximum gross weight (1,305 kips) and 120,000 total departures

A comparison study of Fig. 7 indicates that the pavement design thicknesses according to Eq. 9 are higher by up to about 10% than those from Eq. 8. This finding may be due to the total number of wheels in the main landing gears, which is higher for the A380 (20 wheels) than for the B747 (16 wheels).

The discussions above indicate however, that Eq. 8 seems adequate to calculate pavement-design thicknesses for any given A380 loading, as the A380's ACN values calculated with the aid of this equation comply with the reported values published by the A380 manufacturer. If a safety margin is required, Eq. 9 may substitute Eq. 8. In view of the lack of new full-scale testing data (which are still to come), Eq. 9 (and not Eq. 8) has recently been chosen for upgrading the runways at Israel's Ben-Gurion International Airport. The derived thicknesses were up to 20% larger than those calculated for the B747 utilizing the conventional FAA method, with a gross weight of 873 kips and a total of 120,000 departures (i.e., 6,000 annual departures over a design period of 20 years). This can be seen from Fig 8, which displays final pavement-design curves for these two airplanes. For comparison purposes, this figure also includes the pavement-design curve for the B777 aircraft, which was derived elsewhere in the same manner as described in this paper for the A380 aircraft.

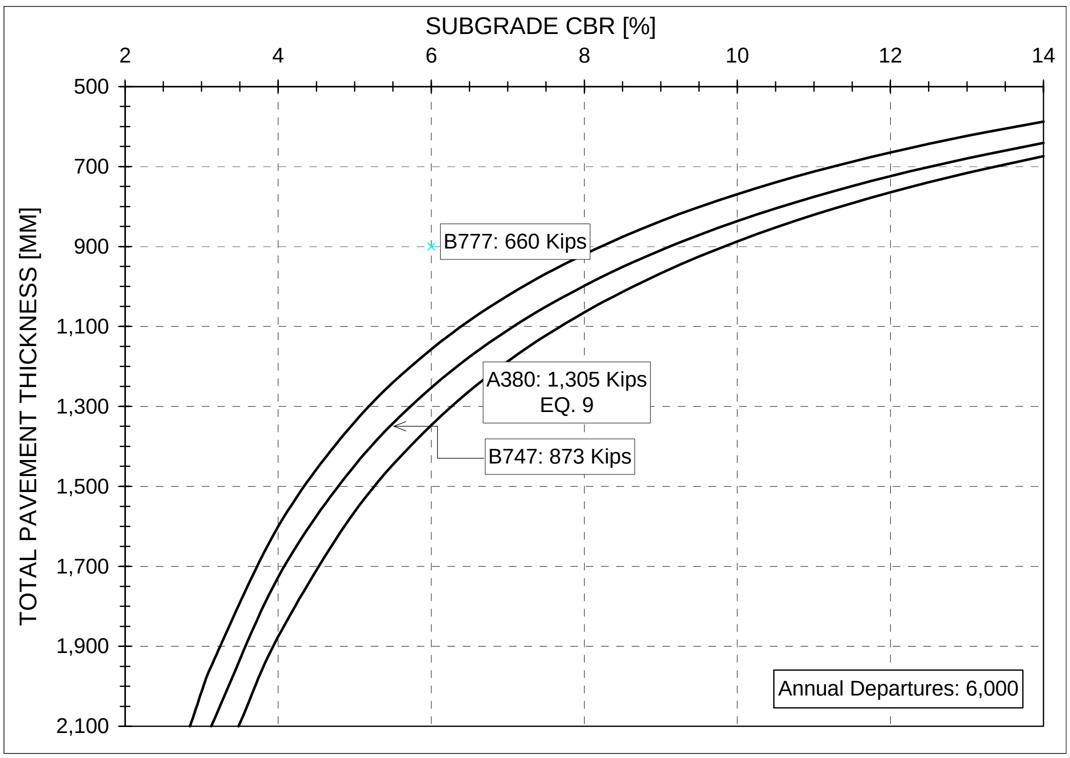

Figure 8. Suggested final pavement-design curves for the A380-800, B777-300, and B747-400 aircraft at their maximum gross weight and 120,000 total departures.

SUMMARY AND CONCLUSIONS

Recently, the arrival of the Boeing B777, which has 6-wheel landing gears, and proposals for other new large aircraft (NLA) have focused attention on pavement-design calculations, which must now take into account their large, multi-wheeled, gear characteristics. It is well known that current pavement-design procedures do not accurately predict the load interaction of the closely spaced landing gears found on these new-generation aircraft. Thus the conventional FAA procedure, which is based on the U.S. Army Corps of Engineers procedure for calculating pavement thicknesses, is not always correct for these new aircraft types (such as the B777 and the A380).

This uncertainty is supported by the fact that thickness-design curves have not yet been included in the preliminary technical publication for the Airbus A380. This preliminary technical publication included, however, the ACN values required for the actual operation of this airplane type at existing airports.

In this context, it should be added that the construction of the National Airport Pavement Test Facility (NAPTF) in Atlantic City (NJ, USA) was based on the need for developing new design procedures for new types of aircraft still to come. For this objective also, the French Airport and Airforce Bases Engineering Department (STBA) and the French Laboratory for Civil Engineering (LCPC) initiated an A380 Pavement Experiment Program (A380 PEP) [17]. In the meantime, however, the construction of new airport pavements, particularly new runways and aprons, has to continue although the predicted fleet-mix includes the new generation of NLA. Thus for the intermediate period, this paper has suggested approximate procedures to calculate the pavement-thickness values for these NLA's, particularly the forthcoming Airbus A380. These approximate procedures will be compatible with the reported ACN values as published by the manufacturers. This paper postulated that for the A380, the LEDFAA procedure is not an adequate substitute for the FAA conventional procedure, if the latter fails to yield reasonable answers. More genaral information concerning the adequacy of the layered elastic computational program and the conventional FAA (or USACE) pavement-design method can be found in the technical literature [18, 19].

Finally this paper has shown the following:

- The reported A380's ACN values as published by the manufacturer are significantly smaller than those calculated by the conventional FAA method (or the conventional USACE method), which utilizes the ESWL concept (Fig. 2) and the load-repetitions factor (Fig. 3); thus the pavement-design thicknesses as derived from the latter design method seem to be much higher than required.
- The modification of the direct regression that was carried out elsewhere on the historical MWHGL tests performed by the U.S. Army Corps of Engineers leads to ACN values, almost identical with all reported ACN values (including those for the B777 and A380 aircraft), with sufficient accuracy.
- The new modified regression equation leads, for the A380 aircraft, to smaller thicknesses compared with those calculated by the derived conventional FAA equation.
- Another approximate method, the ACN equivalent, which is based on the FAA conventional method but for the B747 with an enlarged total weight to represent the ACN reported values for the A380, supports the above results although it yields results that are higher by up to10% for the airplane maximum gross weight and for 120,000 total departures.

The last, new approximate method has recently been utilized for upgrading runways at Israel's Ben-Gurion International Airport. The derived thicknesses were up to 20 % higher than those calculated utilizing the conventional FAA method for the B747, with a gross weight of 873 kips and 120,000 total departures (i.e., 6000 annual departures along a design period of 20 years). If a value other than 120,000 total departures is required, pavement-design equations similar to Eq. 9

can easily be derived.

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